An Investigation of Turbulent Heat Exchange in the Subtropics

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LONG-TERM GOALS

The long-term goal is to improve our understanding of heat and moisture exchange in the tropics through direct estimates of the fluxes and their related mean variables. The flux of heat across the coupled boundary layers is primarily accomplished by small-scale processes that are parameterized in numerical models. The ultimate goal is to improve the Navy's predictive capabilities in the tropics through an improved understanding of the processes driving the Madden-Julian Oscillation (MJO).

OBJECTIVES

The primary objective of this research is to improve the surface flux parameterization for latent and sensible heat used in these models and observational process studies. We will collaborate with researchers from NCAR, NOAA/ETL, Oregon State University, and other institution to investigate the relationship between boundary layer structure and surface forcing during an MJO event. This will be accomplished through measurements collected from a research vessel that conducted surveys during two 30-40 cruises to investigate air-sea interaction during periods when conditions are favorable for MJO formation (Madden and Julian, 1994). The measurement will include surface meteorological and atmospheric vertical structure and collaboration with numerical modelers and other observational components of the program. **The principle hypothesis of this research is that improved observations and parameterizations of latent and sensible heat fluxes, which is a primary source of energy for these convective systems, will improve our ability to simulate and predict the MJO.**

APPROACH

Flux Measurements: The PI (Edson) deployed a Direct Covariance Flux System (DCFS) aboard the R/V Revelle alongside a suite of instruments to measure the short and longwave radiative fluxes, wind speed and direction, temperature, pressure, humidity, and precipitation. The DCFS (Edson et al., 1998) has been used in a number of field programs and would provide estimates of the momentum, sensible heat and latent heat fluxes during ship-based surveys. The PI deployed a newly developed LI-COR LI-7200 infrared gas analyzer that is expected to improve the latent heat flux estimates. This new unit ran alongside the LI-7500 that has been successfully deployed in previous investigations.

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The DCFS have been combined with their associated means and oceanic variables to:

- Provide direct estimates of the air-sea fluxes driving boundary layer evolution and mixed layer response over an annual cycle of MJO events.
- Quantify the spatial variability of atmospheric forcing in the study area.
- Investigation the temporal relationship between SST anomalies, convection (e.g., using satellite date or in situ radiation measurements as surrogates), and latent heating.
- Improve bulk parameterizations of latent and sensible heat fluxes for process studies and boundary condition in numerical models.

The DCFS and infrared hygrometers allow the PI and his colleagues to investigate the exchange of sensible and latent heat between the atmosphere and ocean using the direct covariance method. This method correlates fluctuations in the vertical velocity, w', with fluctuations in the sensible heat, $\rho_a c_p T'$, and latent heat, $\rho_a L_v q'$, per unit volume:

$$Q_{sen} = \rho_a c_p \overline{w'T'} \tag{1}$$

$$Q_{lat} = \rho_a L_v \overline{w'q'} \tag{2}$$

where ρ_a is the density of air, c_p is the specific heat of air, L_v is the latent heat of vaporization, T' and q' are temperature and specific humidity fluctuations, respectively; and the overbar denotes a time average ranging between 10-30 minutes for turbulent fluxes. The sensors are capable of accurately measuring fluctuation at approximately 2 Hz to capture the total flux near the air-sea interface.

Unfortunately, this direct method is generally difficult to implement over the ocean due to platform motion, flow distortion and sensor limitations. Instead, oceanographers and meteorologists often rely on bulk formula such as the COARE 3.0 algorithm (Fairall et al., 1996; 2003) that relates the fluxes to more easily measured averaged wind speed, temperature and humidity. These averaged variables are related to the flux through transfer coefficients. This same approach is commonly used to parameterize the surface fluxes in forecast models from variables resolved by the model. For example, based on the dimensional arguments, the exchange of sensible and latent heat at the ocean surface is expected to go as the wind speed time the air-sea temperature and humidity differences, respectively:

$$Q_{sen} \cong -\rho_a c_p C_H U_r \Delta\Theta \tag{3}$$

$$Q_{lat} \cong -\rho_a L_v C_E U_r \Delta Q \tag{4}$$

where C_H and C_E are the transfer coefficients for heat and mass known as the Stanton and Dalton numbers, respectively; U_r is the wind speed relative to water (i.e., the wind speed-current difference); and $\Delta\Theta$ and ΔQ are the mean air-sea potential temperature and specific humidity. The uncertainty in the transfer coefficients for heat and mass remains one of the main obstacles to accurate numerical forecasts. Improvement of these transfer coefficients is a primary objective of this research.

WORK COMPLETED

Preliminary: In preparation for the field work in the fall of 2011, the PI combined heat flux estimates from a number of recent field programs to look at the behavior of the transfer coefficients from prior experiments. These field programs including the ONR sponsored CBLAST program (Edson et al. 2007) and the NSF sponsored CLIMODE (Marshall et al. 2009) and GASEX programs. The CBLAST-LOW experiments were primarily conducted in low to moderate winds while the CLIMODE and GASEX experiments focused on air-sea interactions at moderate to high winds. The combined data set therefore covers a wide range of wind and stability conditions. For example, near surface winds of 15 m/s were commonly encountered over the North Atlantic during CLIMODE and the data set includes wind events with speeds over 25 m/s. These high wind events drive surface stresses that routinely exceed 1.0 N/m^2 and combined latent and sensible heat fluxes from the ocean into the atmosphere that exceed 1200 W/m^2. These enormous heat fluxes are driven by high winds and large air-sea temperature and humidity differences encountered over the Gulf Stream during cold air outbreaks. The CBLAST-LOW program collected 3 months of data from an Air-Sea Interaction Tower (ASIT) under low to moderate wind conditions. To data, the CBLAST investigations have focused on the role of swell on momentum exchange under low wind conditions while the CLIMODE investigations have focused on momentum exchange at high winds. This investigation focuses on heat exchange from low to high winds using the combined data sets. Preliminary results from this investigation were reported at the AMS 17th Conference on Air-Sea Interaction in Annapolis, MD.

Main Experiment: The PI (Edson) deployed a turbulent and radiative flux package and associated mean meteorological sensors aboard the research vessel the R/V Revelle during the DYNAMO field program. In situ meteorology and high-rate flux sensors operated continuously while in the sampling period for DYNAMO Leg 3. This included all sensors operating during Leg 2 with the addition of a closed-path LI-7200 IRGA to the flux systems. Sea surface temperatures were measured by the group using the sea-snake floating thermistor and radiometric estimates of skin temperature in collaboration with Chris Zappa (LDEO/Columbia). NOAA/PSD operated a suite of remote sensing instruments for low clouds and light precipitation: the NOAA W-band cloud radar, a microwave radiometer, and a laser ceilometer. Aircraft overflights were made on November 13, 22 and 26 with all systems operational and good relative winds for our flux measurement systems.

Overall, these packages ran continuously in international waters from 4 September (start of Leg 1) to 31 December, 2011 (end of leg 4). The data return rate was nearly 100%. Preliminary results from the field campaign were reported at the AMS 18th Conference on Air-Sea Interaction in Boston, MA.

RESULTS

Preliminary Research: The CBLAST measurements indicate that the directly measured fluxes are somewhat lower than C3.0 when the latent heat flux is positive (corresponding to an upward moisture flux), but are significantly different than C3.0 when the latent heat flux is negative (corresponding to a downward moisture flux). The downward latent heat flux is often associated with fog and stable conditions. However, the CBLAST data indicates that the Dalton number (i.e., the transfer coefficient for latent heat) is still smaller that C3.0 even after removal of downward fluxes and foggy periods. This is in good agreement with the results from both the CLIMODE and GASEX programs as shown in Figure 1. Therefore, the COARE 4.0 algorithm proposes a neutral Dalton number that is 20% lower than the COARE 3.0 algorithm at low to moderate wind speeds. However, there are significant differences between the data sets at moderate to high winds

On the other hand, the Stanton number (i.e., the transfer coefficient for sensible heat) is in reasonable agreement with COARE 3.0 below 15 m/s for all three data sets as shown in Figure 2. This result argues against the commonly held assumption that the neutral transfer coefficients for heat and mass are equal. However, there is significantly more scatter in these results and the CBLAST and GASEX results again show different behavior at unstable versus stable data (not shown). Validation of the reduced Dalton number, confirmation of the observation that heat and mass transfer coefficients are not equal, and reduction of the uncertainty in these parameterizations is anticipated from the carefully conducted measurements we expect from the field program.

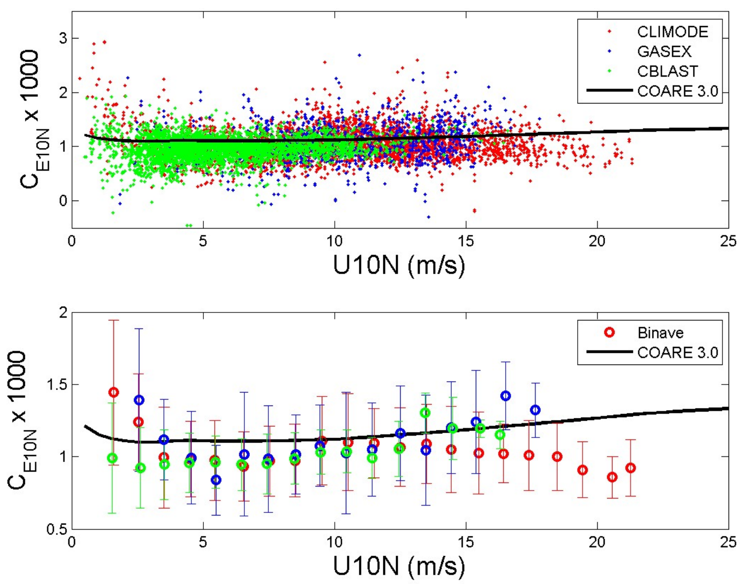

Figure 1. Bin-average estimates of the neutral Dalton number using latent heat fluxes measured during the CBLAST, CLIMODE and GASEX programs.

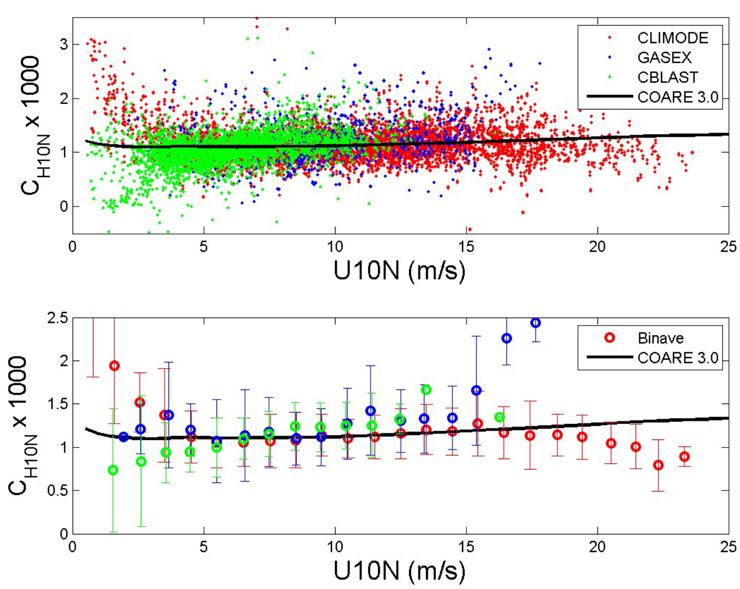

Figure 2. Bin-average estimates of the neutral Stanton number using sensible heat fluxes measured during the CBLAST, CLIMODE and GASEX programs.

Main Experiment – ONR Leg #3: The observational highlight of Leg 3 was the capture of an almost complete MJO cycle in our time series measurements. After a brief period of convective activity upon arrival, the measurements were characteristic of the suppressed phase of the MJO. Strong solar heating of the ocean overwhelmed the convective cooling by the atmosphere, and ocean surface temperature increased by approximately 1°C between 11-17 November (Yeardays 315-321). As shown in Figure 3, winds remained light and variable during this period and little precipitation was observed. In Figure 3, the velocity data were taken from the sonic anemometers on the forward mast. Poor relative wind directions were removed and the data was interpolated through these periods. Surface currents were collected from the ship's ADCP after QC by the OSU mixing group. Air temperature was collected by two aspirated T/RH sensors on the bow. Poor relative wind directions were also removed from these data to reduce the heat island effect of the ship. Sea surface temperature was measured by the sea-snake and corrected for cool-skin effects. Precipitation (P) was provided by an optical rain gauge after calibration with 6 other rain gauges (see below). Specific humidity was calculated by combining these sensors with pressure measurements. Evaporation (E) was computed using the latent heat flux estimated by the COARE 3.0 algorithm. Accumulated totals of P and E are shown. The blue shaded area is therefore their difference.

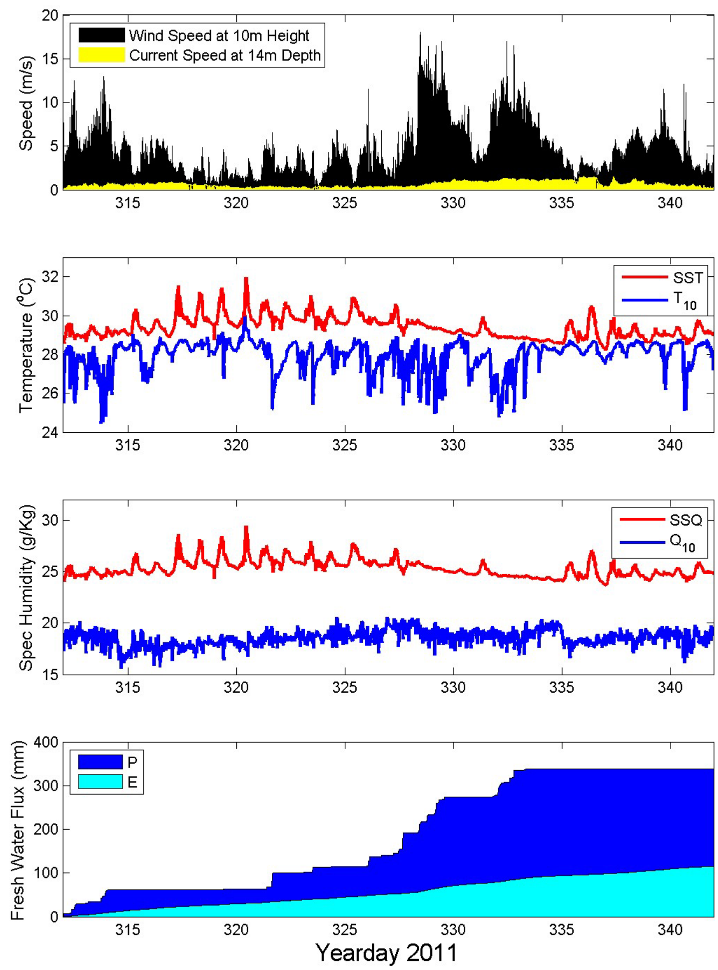

Figure 3. Time series of mean meteorological and ocean surface variable during Leg 3.

Atmospheric convection began to increase on 17 November (Yearday 321) with precipitation falling overnight. Wind speeds and convection gradually increased during the period between 18-23 November (Yeardays 322-327). Sea surface temperatures leveled off during this period due to a gradual reduction in solar radiation and continued latent heat loss of approximately 100 Wm^{-2}. The active phase of the MJO was in full swing with the arrival of cyclone aided westerly wind burst on 24 November (Yearday 328). Ten-minute averaged wind speeds in excess of 19 m/s where observed over growing seas with significant wave heights of approximately 3 m. The sea-surface temperature dropped significantly during this period with combined sensible and latent heat loss to the atmosphere of approximately 200-400 Wm^{-2}. Moderate winds, precipitating convection and surface cooling continued through the end of November (Yearday 334). Overall, precipitation exceeded evaporation during this period. Although westerly surface winds around 5 ms^{-1} continued into December, a drying out of the atmosphere aloft and associated reduction in convective activity was observed as the active phase of the MJO-related convection moved towards the maritime continent.

Surface Fluxes: A summary of the latent, sensible, radiative and net heat fluxes are shown in Figure 4. The downward radiative fluxes were measured by the purgeometers (LW) and pyranometers (SW) located on the top of the forward mast. The upward long-wave radiation was obtained using our SST measurements and corrected for IR reflection from downwelling long-wave. A commonly used parameterization of sea-surface albedo was used to estimate the reflected solar. The optimized set of mean meteorological and surface ocean measurements (temperature and currents) are used to compute the latent, sensible and rain fluxes with the COARE 3.0 algorithm.

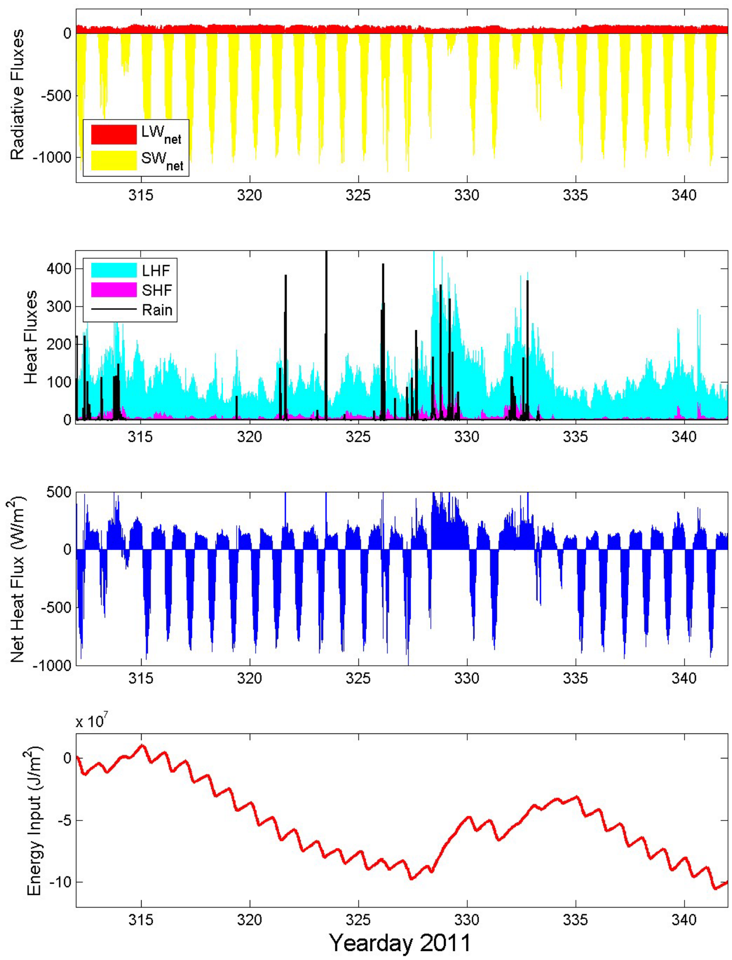

Figure 4. Time series of radiative, surface heat and net heat fluxes during Leg 3. The lower panel shows the integral of the net heat flux over the experiment. A small correction (~1% reduction) was applied to the short-wave measurements from the forward mast based on comparison with the PSD and OSU sensors. A more significant correction to the long-wave measurements was applied to the mast using the PSD sensors. The latent, sensible and rain induced fluxes are computed using COARE 3.0.

The lower plot in Figure 4 shows the integrated value of the net heat flux into the ocean. The large amount of heat supplied to the ocean during the suppressed phase of the MJO is clearly seen in the measurements between 11-20 November (Yeardays 315 and 324). It is important to note that not all of this energy goes into heating of the mixed layer as a significant fraction of the solar radiation penetrates through this layer. Oceanic turbulence also removes some of the heat through the base of the mixed layer. However, this still represents a significant amount of energy stored by the oceanic capacitor to potentially initiate (in tandem with favorable atmospheric condition, e.g., surface convergence and divergence aloft) and drive convection during the active phase of the MJO. This plot also shows a leveling off of the heating around 21 November (Yearday 325), which likely corresponds to the start of the active phase. The westerly wind burst is clearly associated with the active phase, and drove the net heat loss evident between 24 November and 1 December (Yeardays 327 and 335) and associated cooling of the ocean. The end of the time series again shows the heat supplied to the

ocean (i.e., recharging of the capacitor) during the start of a new suppressed phase. The rate of energy input is very similar to the prior period and represents the clear sky solar value integrated over a day minus the nominal value of latent heat flux of approximately 100 Wm^{-2}. The role that the ocean and air-sea exchange plays in driving the amplitude and phase of the MJO will be a focus of our collaborative investigation with the Ocean Mixing, Sounding and Remote Sensing groups.

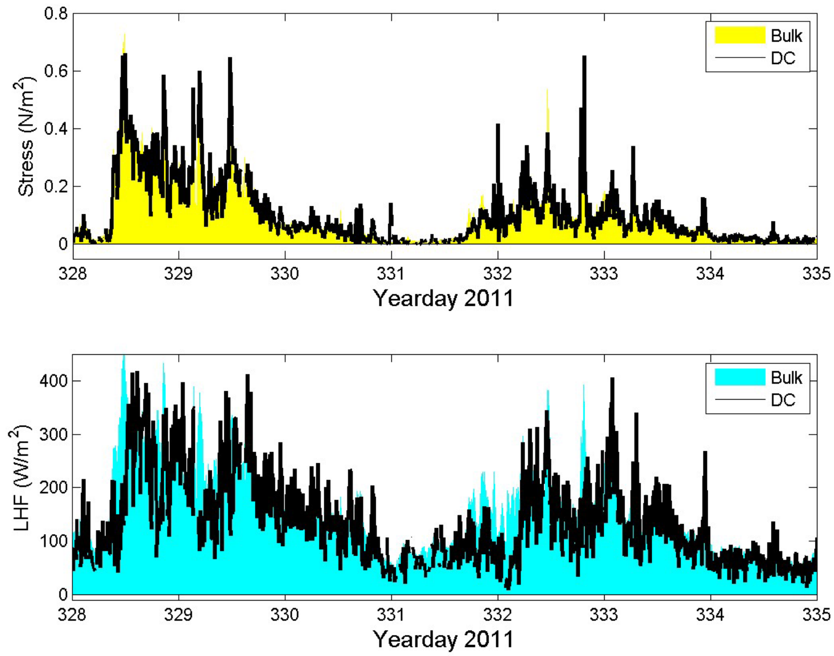

Figure 5. Time series of surface stress (top) and latent heat flux (bottom) derived from the direct covariance and bulk aerodynamic methods. The solid color is the bulk and the black line is the direct measurements.

A primary goal of our research is to improve the surface flux parameterization for latent and sensible heat used in these models and observational process studies. Specifically, continued improvement to and validation of the COARE algorithm is also a goal of the experiment. This was accomplished by the successful deployment of 3 flux packages on the forward mast of the R/V Revelle. This included a new version of a closed path infrared hygrometer that continued to measure the moisture flux through rain events. These packages operated successfully during the Legs 2 through 4 collecting approximately 65 days of fluxes and their associated means.

The flux group has begun to process the turbulence instrumentation on the forward mast to compute fluxes using the direct covariance (eddy correlation) method after correction for ship motion. Preliminary results from our analysis are encouraging. For example, Figure 5 shows a time series of surface stress and latent heat flux estimated from the direct covariance method and COARE 3.0 bulk algorithm during the westerly wind burst. In this figure, the solar background color represents the bulk estimates, while the solid line represents the DC measurements. The DC measurements are limited to more favorable relative wind directions to result the impact of flow distortion on our measurement. Nonetheless, the agreement between the two stress estimates is very good. The comparison between

the latent heat fluxes shows good agreement, but there are more obvious discrepancies between the estimates that require further investigations. However, it is promising to note that the closed-path IRGA deployed for this leg continued to measure fluxes while it was raining. In fact, some of the discrepancies in the data may be driven by physical processes that occur during these rain events that are not included in the bulk algorithm.

Our ongoing investigations focus on the improvement of the COARE 3.0 algorithm using our directly measured Stanton and Dalton numbers. As stated above, the COARE 3.0 coefficients of sensible heat and moisture are assumed to be the same, suggesting similarity in the transfer of heat and mass. However, it now appears more accurate to model the fluxes of heat and moisture with separate formulae based on the CBLAST, CLIMODE and GASEX and preliminary DYNAMO results. The ultimate goal of this research is the development of the COARE 4.0 algorithm.

IMPACT/APPLICATIONS

None to date

TRANSITIONS

None to date

RELATED PROJECTS

The ONR portion of this program will work closely with investigators from the NSF/NOAA funded DYNAMO program. The results will also be compared with findings from the NASA/SPURS program.

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